Measurements of fundamental fluid physics of SNF canisters

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With the University of Idaho, Ohio State University and Clarksean Associates, this research program has the long-term **goal** to develop reliable predictive techniques for the energy, mass and momentum transfer plus chemical reactions in drying / passivation (surface oxidation) operations in the transfer and storage of spent nuclear fuel (SNF) from wet to dry storage. Such techniques are needed to assist in design of future transfer and storage systems, prediction of the performance of existing and proposed systems and safety (re)evaluation of systems as necessary at later dates.

Many fuel element geometries and configurations are accommodated in the storage of spent nuclear fuel. Consequently, there is no one generic fuel element / assembly, storage basket or canister and, therefore, no single generic fuel storage configuration. One can, however, identify ***generic flow phenomena or processes*** which may be present during drying or passivation in SNF canisters. The **objective of the INEEL tasks was to obtain fundamental measurements** of these flow processes in appropriate parameter ranges.

With the University of Idaho, an idealization of a combined drying and passivation approach has been defined in order to investigate the generic flow processes. This simulation includes flow phenomena that occur in canisters for high-enrichment and medium-enrichment fuels, where fuel element spacing in the canister is increased as compared with low enrichment fuel. As shown in Figure 1, canister diameter was taken as 46 cm (18 in.) and a single basket of about 1.2 meters (4 ft.) length was considered. A long central tube ("dip tube") served as the inlet as in one earlier concept for a passivation process; while this concept apparently has not yet been selected for application, it provides an excellent example of the coupled, complex phenomena which may be present in canister flows. Suggested design flow rates for this hypothesized application indicate that the Reynolds number in the inlet tube would be expected to be between 2500 and 5000, i.e., relatively low, and $Re_{D,h}$ for the fuel element array would be of the order of 100.

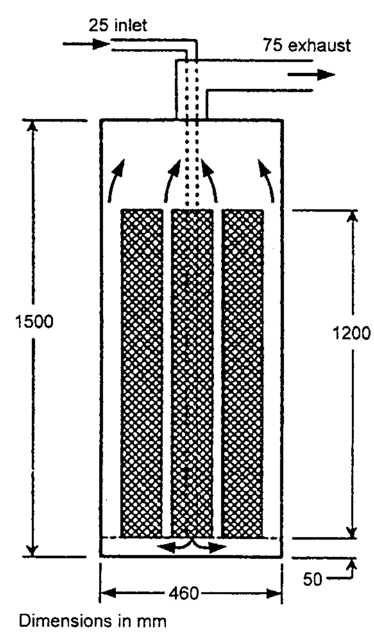

Figure 1. Schematic diagram of idealized SNF canister for study of generic flow processes occurring in drying and/or passivation.

The local distributions of convective mass transfer characteristics (drying/passivation) are expected to depend on the freestream turbulence in the flow around stored fuel elements. The magnitudes of this turbulence depend on the turbulence distributions on the upstream side of the perforated basket support plate ("inlet plenum") and, in turn, in the impinging jet and in the inlet tube.

The INEEL efforts emphasized **two tasks**:

- **Overall flow visualization for a variety of configurations**
  and
- **Pointwise turbulence and velocity measurements** with two-component laser Doppler velocimetry in the unique INEEL Matched-Index-of-Refraction flow system

This information can assist engineers in understanding variations of surface drying and passivation through an array and approaches to modify designs to counter non-uniformities and to improve distribution, as well as providing bases for assessment of computational fluid dynamics codes proposed for the purpose.

A ***water-flow experiment with a 3/4-scale model*** (relative to the idealized canister) has been used for **overall flow visualization** and velocity measurements, with and without an array of simulated fuel elements. Observations have been made with perforated plates (representing basket support plates) having three hole geometries, with and without simulated fuel elements. Streamline and velocity vector plots were developed. The flow patterns exhibited are very complex and provide a non-uniform flow distribution along the simulated fuel elements. Experiments were conducted to determine the canister flow field with three perforated plates with open areas of fifty, eight and four per cent (porosities). Experiments reported are primarily for $Re_{inlet} = 2{,}500 \pm 100$.

The flow is approximately circumferentially-periodic and symmetrical about cross-sections through the four simulated elements for experiments using each of the three perforated plates. With a plate open area of fifty per cent, the flow pattern is comparable to that of a submerged impinging jet on a ***semi-infinite plate*** with formation of a single large vortex and entrainment and recirculation through the holes in the perforated plate near the center. With the plates having open areas of four per cent and eight per cent, recirculation regions occur downstream of the perforated plate and ***two*** main ***recirculation zones*** (plus a small corner flow vortex) form upstream of the perforated plate. In these cases the flow pattern in the inlet plenum has some features of a ***confined impinging jet*** .

The Reynolds number (based on hydraulic diameter) in the array downstream of the plate is approximately 70 for $Re_{inlet} = 2{,}500$. With the tubes present, vortices persist for the majority of the tube bundle length and the flow only starts to approach a fully-developed laminar profile near the exit of the basket ($L/D_h \approx 6$). The flow distribution is uneven near the surface of the simulated fuel elements. These experiments show flow across the simulated elements and resultant vortex shedding, although the vortices do not show the clear alternating pattern of a Karman vortex street.

Velocity and turbulence distributions were measured with laser Doppler velocimetry in the unique INEEL Matched-Index-of-Refraction (MIR) flow system. An advantage of this facility is the capability of obtaining optical fluid mechanics data without optical distortion and without disturbing the flow by inserting a physical sensor. A ***0.6-scale model*** of the idealized canister was employed with dimensions as follows: plenum spacing $H/D = s/D = 2$, canister internal radius $r_o/D = 9$, pitch of holes in the perforated plate $p_h/D = 1$ and hole diameter $d_h/D = 1/4$ in a square pattern (Figure 2). Most measurements were taken at $Re_{inlet} = 2510$. This part of the study concentrated on flow in the inlet tube, the impinging jet and flow upstream of the perforated plate (inlet plenum).

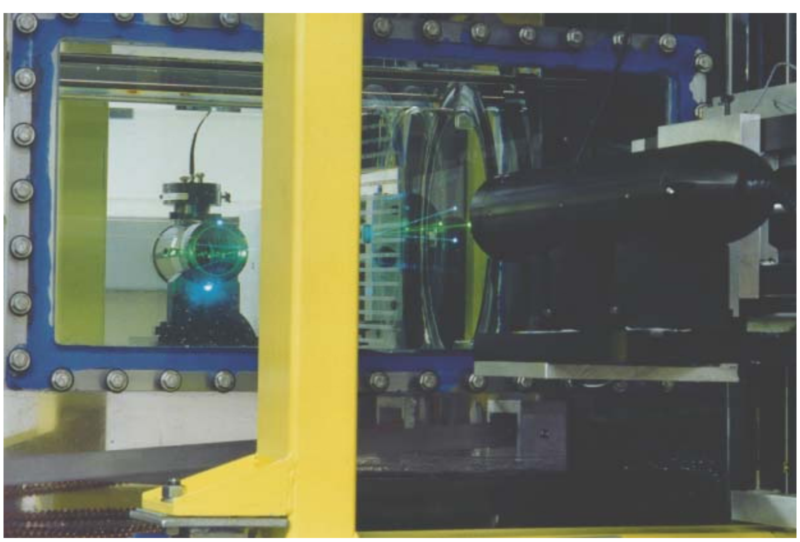

Figure 2. Model of idealized SNF canister installed horizontally in MIR test section. Perforated holes in simulated bottom support plate are barely seen at some wave lengths in the visible spectrum; the black ring is a gasket sealing the acrylic end plate.

Measurements included the mean distributions of radial and axial velocity components, ***V and U***, and their root-mean-squared fluctuations, ***v' and u'*** (Figure 3). Main features of the flow in the inlet plenum upstream of the perforated plate are the high velocity impinging jet, the thin expanding wall jet, a single recirculating eddy near the outer wall of the canister and relatively low velocities near the perforated plate. The flow in the wall jet remains attached until it impinges on the outer wall of the plenum region and induces the main recirculating eddy. In the plenum region upstream of the perforated plate, the radial velocity component at a point is generally greater than the axial component, except in the recirculating eddy. The rms radial velocity fluctuations are generally considerably larger than the rms axial fluctuations. The large relative values of v' imply the likelihood that there are considerable fluctuations in the incident angle as the flow approaches the holes in the perforated plate; this situation differs significantly from flow conditioning applications of perforated plates in wind tunnels.

General comparison of the results for three different situations at the same Reynolds number showed that flow in the plenum region upstream of the perforated basket support plate is sensitive to the inlet flow characteristics in the expected range of Reynolds numbers and to the geometry of the perforated plate. It is recommended that the present data be used to assess capabilities of existing and proposed CFD (computational fluid dynamics) codes which are intended to predict behavior in SNF canisters. While proprietary codes for predicting drying supposedly have been validated for the nuclear reactor industry, it is not clear that these "validations" have been at appropriate Reynolds numbers and geometrical ranges or how close the predictions were to any measurements (since they are "proprietary"). It would be desirable to test such codes by comparison to these measurements.

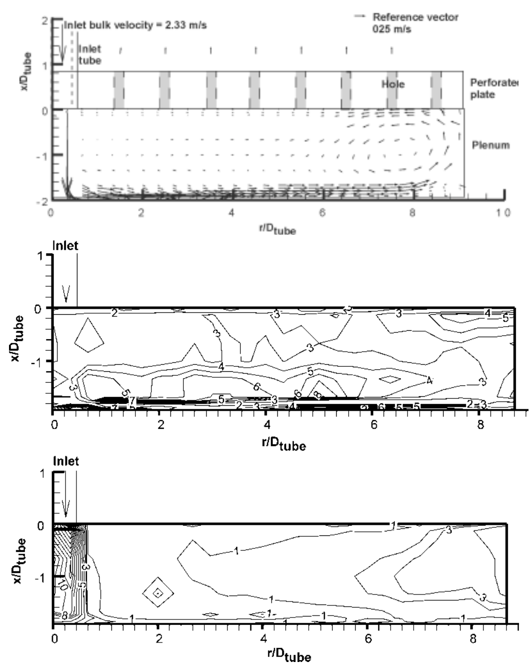

Figure 3. Distributions of mean and fluctuating velocities for a semi-confined impinging jet and its surroundings: (a) mean velocity vectors, (b) rms radial component, $u'/V_{b,in}$, (c) rms axial component, $v'/V_{b,in}$ [Condie, McCreery and McEligot, 2001; McCreery et al., 2002].

It is apparent from these experiments that, despite the conceptual simplicity of the **canister** design, the **flow pattern is very complex**. Of possible concern is the uneven flow distribution near the surface of the simulated fuel elements as demonstrated in the water flow visualization experiments. A more even flow distribution is expected to provide more uniform drying and passivation around the elements. Possible design changes that could provide more uniform distributions (if that is desirable) include (1) an optimized distribution of perforated plate holes, (2) a longer inlet plenum length (to decrease radial velocity tangent to the perforated plate which will presumably provide a more even flow distribution) and (3) a higher packing density of fuel elements, where nuclear criticality considerations allow. The canister and plate geometry could be optimized using a CFD code once it has been verified that the code can reasonably predict the present (and other) experiments.

Additional ***lessons learned*** for design of drying/passivation systems may be summarized

- Bypass flow routes should be avoided
- Flow distribution should be controlled
- Assumptions of uniform flow could be misleading

- Previous measurements of flow through perforated plates for wind tunnel conditioning are not likely to be applicable to basket support plates
- Modifications of basket support plates and lower regions of canisters could be useful to distribute turbulent flow to the elements
- Use caution when applying commercial, general purpose CFD codes using popular turbulence models.

Publications and presentations

McCreery, G. E., K. G. Condie, R. L. Clarksean and D. M. McEligot, 2002. Convective processes in spent nuclear fuel canisters. ***Heat Transfer 2002*** (Proc., 12th Int. Heat Transfer Conf., Grenoble), Vol. 4, pp. 663-668.

Clarksean, R. L., J. C. Crepeau and D. M. McEligot, 2002. Computational modeling of the fluid flow in a representative spent nuclear fuel canister. Annual Meeting, Amer. Nuclear Soc., Hollywood, Fla., June.

Stoots, C. M., S. Becker, K. G. Condie, F. Durst and D. M. McEligot, 2001. A large-scale matched-index-of-refraction flow facility for LDA studies of complex geometries. ***Exp. Fluids***, 30, pp. 391-398.

Condie, K. G., G. E. McCreery and D. M. McEligot, 2001. Measurements of fundamental fluid physics of SNF storage canisters. Tech. rpt. INEEL/EXT-2001-1269.

McCreery, G. E., K. G. Condie, J. C. Crepeau, R. Clarksean, Y. G. Guezennec, R. S. Brodkey and D. M. McEligot, 1999. Flow visualization and velocity measurements in a model fuel storage canister. Global '99 - International Conference on Future Energy Systems, Jackson, Wyo., August.

McEligot, D. M., J. C. Crepeau, H. M. McIlroy, S. Reese, G. E. McCreery, K. G. Condie, Y. G. Guezennec, R. S. Brodkey and R. L. Clarksean, 1998. Fluid mechanic studies relating to drying and passivation in an idealized SNF canister. ANS 3rd Topical Meeting on Spent Nuclear Fuel and Fissile Material Management, Charleston, S. C., September.